

The Telesupervised Adaptive Ocean Sensor Fleet (TAOSF) Architecture: Coordination of Multiple Oceanic Robot Boats

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Abstract—Earth science research must bridge the gap between the atmosphere and the ocean to foster understanding of Earth's climate and ecology. Ocean sensing is typically done with satellites, buoys, and crewed research ships. The limitations of these systems include the fact that satellites are often blocked by cloud cover, and buoys and ships have spatial coverage limitations. This paper describes a multi-robot science exploration software architecture and system called the Telesupervised Adaptive Ocean Sensor Fleet (TAOSF). TAOSF supervises and coordinates a group of robotic boats, the OASIS platforms, to enable in-situ study of phenomena in the ocean/atmosphere interface, as well as on the ocean surface and sub-surface. The OASIS platforms are extended deployment autonomous ocean surface vehicles, whose development is funded separately by the National Oceanic and Atmospheric Administration (NOAA). TAOSF allows a human operator to effectively supervise and coordinate multiple robotic assets using a sliding autonomy control architecture, where the operating mode of the vessels ranges from autonomous control to teleoperated human control. TAOSF increases data-gathering effectiveness and science return while reducing demands on scientists for robotic asset tasking, control, and monitoring. The first field application chosen for TAOSF is the characterization of Harmful Algal Blooms (HABs). We discuss the overall TAOSF architecture, describe field tests conducted under controlled conditions using rhodamine dye as a HAB simulant, present initial results from these tests, and outline the next steps in the development of TAOSF.¹²

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1. INTRODUCTION

Earth science research requires information obtained from space, the atmosphere and the ocean to foster understanding of the Earth and its natural processes. Developing a better understanding of ocean processes, in particular, is crucial for global warming, meteorological and ecological studies. Ocean sensing is typically done with satellites, buoys, airborne assets and crewed research vessels. Satellites and airplanes are limited by cloud cover and temporal/geographical coverage and resolution, while research vessels are expensive to deploy, and buoys cannot be self-deployed to specific areas of interest.

The National Oceanic and Atmospheric Administration (NOAA) is addressing some of these constraints through the development of robotic ocean boats for weather-related ocean monitoring. The OASIS (Ocean-Atmosphere Sensor Integration System) vessels are long-duration solar-powered autonomous surface vehicles (ASVs), designed for global open-ocean operations (Figs. 1, 4, 5). One of the key objectives of our research is to enhance the science value of multiple robotic sensing assets such as the OASIS vessels by coordinating their operation, adapting their activities in response to sensor observations, and allowing a human operator to oversee multiple assets with minimal effort.

This paper describes a multi-robot science exploration software architecture and system called the Telesupervised Adaptive Ocean Sensor Fleet (TAOSF). TAOSF supervises and coordinates a group of robotic boats, the OASIS platforms, to enable in-situ study of phenomena in the ocean/atmosphere interface, as well as on the ocean surface

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² IEEEAC paper #1293, Version 3, updated 2007:12:22

and sub-surface.

The TAOSF system is applicable to the study of dynamic processes such as coastal pollutants, oil spills, hurricanes or harmful algal blooms. More generally, it can be used in a variety of areas where multiple sensing assets are needed, including ecological forecasting, water management, carbon management, disaster management, coastal management, homeland security, and planetary exploration.

The first field application chosen for TAOSF is the characterization of Harmful Algal Blooms (HABs). In the following sections, we will discuss the overall TAOSF architecture, introduce the HAB problem, describe field tests conducted under controlled conditions using rhodamine dye as a HAB simulant, present initial results from these tests, and outline the next steps in the development of TAOSF.



Figure 1. Artist's concept of the OASIS robot vessels investigating the nature and extent of a Harmful Algal Bloom (HAB).

2. TAOSF ARCHITECTURE

The TAOSF architecture (Fig. 2) provides an integrated approach to multi-robot coordination and sliding robot-human autonomy. It allows multiple mobile sensing assets to function in a cooperative fashion, and the operating mode of different vehicles to vary from autonomous control to teleoperated control.

TAOSF supports the following features:

- **Sliding autonomy**, allowing an operator to control the vehicles by setting high-level goals, such as specifying an area to monitor, or by taking direct control of the vehicles via teleoperation, or at other autonomy levels in between.
- **Adaptive replanning** of the activities of the OASIS

vessels based on sensor inputs (dynamic sensing) and **coordination between multiple assets**, thereby increasing data-gathering effectiveness while reducing the effort required for tasking, control, and monitoring of the vehicles.

- **Web-based communications** permitting control and communications over long distances and the sharing of data with remote experts.
- **Autonomous hazard and assistance detection**, allowing automatic identification of hazards that require human intervention to ensure the safety and integrity of the robotic vehicles, or of science data that require human interpretation and response.
- **Onboard science analysis** of the acquired data in order to perform an initial assessment of the presence of specific science signatures of immediate interest.

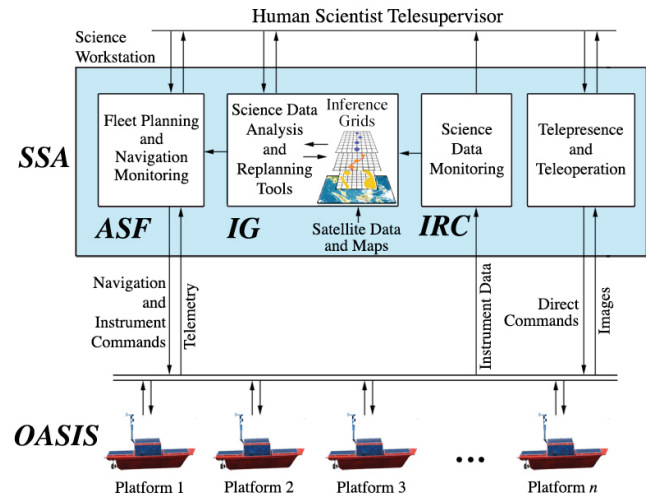


Figure 2. The TAOSF architecture.

The TAOSF software architecture (Fig. 2) integrates and extends five subsystems developed by the participating institutions. The five TAOSF components (Fig. 3) are listed below:

1. The **OASIS Autonomous Surface Vehicle (ASV) System** includes the vessels themselves as well as the land-based control and communications infrastructure which has been developed for them. The OASIS platform software directly controls the hardware of each boat (sensors, actuators, etc.), and also provides a low-level waypoint navigation capability. This system has been developed by Emergent Space Technologies (EST) working with the team members at the NASA Wallops Flight Facility (WFF), where the platforms are built and maintained.
2. The **Multi-Platform Simulation Environment** has been developed by NASA Goddard Space Flight Facility (GSFC) as a surrogate for the OASIS ASV system, allowing independent development and testing of the higher-level software components.

3. The **Platform Communicator** acts as a proxy for both actual and simulated platforms. It translates platform-independent messages from the higher control systems to the device-dependent communication protocols. This component, developed by GSFC, enables the higher-level control systems to interact identically with heterogeneous actual or simulated platforms.

4. The **Adaptive Sensor Fleet (ASF)** provides autonomous platform assignment and path planning for area coverage surveys, as well as monitoring of mission progress. The ASF is developed by GSFC.

5. The **System Supervision Architecture (SSA)** provides high-level planning, monitoring, and telesupervision, as well as analysis of science data from both the OASIS platforms and external sources such as satellite imagery and fixed sensors. These data are used by the SSA to plan vessel navigational trajectories for data gathering. The SSA also provides an operator interface for those occasions when a scientist desires to exert direct monitoring and control of individual boats and their instruments. The SSA is based on the Robot Supervision Architecture [1, 2, 3, 4] developed by CMU and JPL.

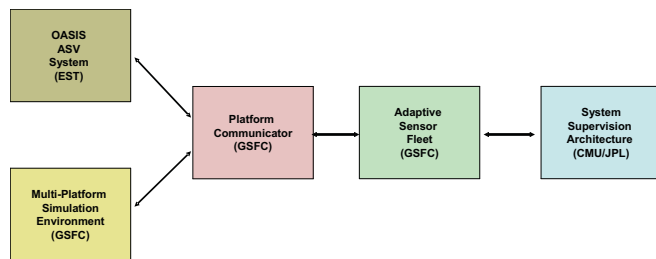


Figure 3. Software components of the TAOSF architecture.

Our initial development effort has concentrated on the integration of these subsystems. We have demonstrated end-to-end integration of SSA, ASF and OASIS in a dry-boat test in May of 2007, and executed integrated in-water tests in the Chesapeake bay in June and August of 2007.

3. OASIS PLATFORMS AND INFRASTRUCTURE

The NOAA-funded OASIS Platform Build Team, which consists of EG&G, Zinger Enterprises, and Emergent Space Technologies, provides vehicle development, payload integration and testing, operations, and maintenance of the OASIS fleet and ground systems. The OASIS platform itself is a long-duration solar-powered autonomous surface vehicle (ASV), designed for autonomous global open-ocean operations (Fig. 4). The platform is approximately 18 feet long and weighs just over 3000 lbs. The vehicle has a payload capacity of 500 lbs, and is designed to be self-righting to ensure survivability in heavy seas. It supports a wide range of communication links including spread spectrum radio, a cellular phone link, and an Iridium satellite link.

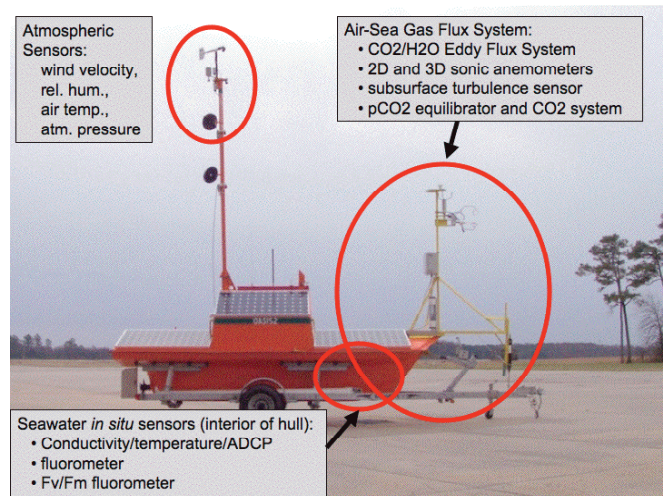


Figure 4. The OASIS boat with its primary sensor systems.

Two platforms (named OASIS1 and OASIS2) are currently undergoing testing at WFF and will support operations for the TAOSF project. Additional platforms are under production. OASIS shakedown operations have been performed since early 2005 in the waters of the DELMARVA region, including the Chincoteague Bay and Pocomoke Sound. The first open-ocean deployment of the OASIS system was performed in November 2006 (Fig. 5). During this operation, the OASIS2 platform successfully navigated over 8 nautical miles on a transect line established in the Atlantic Ocean off the coast from WFF. OASIS1 and OASIS2 are currently undergoing upgrades, sensor integration, and testing in preparation for endurance trials and science operations.



Figure 5. First open-ocean deployment of an OASIS platform, November 2006.

Sensors onboard the OASIS2 platform enable the collection of water salinity and conductivity data, sea surface temperature, and chlorophyll measurements. A rhodamine fluorometer was integrated to support mapping operations during dye deployment tests. The forward payload bay

provides space for installation of additional sensors. This bay includes a water flow-through system with manifolds and a de-bubbling system which simplifies installation of new sensors.

A mast-mounted meteorological station allows acquisition of atmospheric measurements, including barometric pressure, air temperature, relative humidity, wind speed, and wind direction. OASIS2 is also equipped with a forward-looking digital imaging system providing remotely located scientists with images of atmospheric and sea state conditions (Fig. 14).

The off-board infrastructure developed by EST is known as the OASIS Mission Operations Environment (MOE). The MOE resides in the Wallops Coastal Ocean Observation Laboratory (WaCOOL) control room and provides applications and services that enable the WFF engineering and science operations team to perform platform commanding and telemetry monitoring, as well as communications management. The MOE also provides a middleware interface to enable other customers, such as the TAOSF project, to integrate new systems that further enhance OASIS science operations.

4. HARMFUL ALGAL BLOOMS

Interest in Harmful Algal Bloom (HAB) detection has grown in recent years for scientific, commercial and public health reasons. Depending on the type of algae present, HABs have been shown to be dangerous to sea life and to human health.

The Woods Hole Oceanographic Institute (WHOI) has mapped the distribution of *Alexandrium fundyense* cysts in the sea floor of the Gulf of Maine [5]. The Florida Fish and Wildlife Research Institute is analyzing a historical database of concentrations of the HAB dinoflagellate *Karenia Brevis* in Florida waters [6], while the Northwest Fisheries Science Center is developing probes for detecting toxins produced by different species of *Pseudo-nitzschia* [7].

There is a significant interest in identifying environmental factors that contribute to the occurrence of HABs, so that these may be incorporated in bloom prediction algorithms. A regional study on the dinoflagellate *Karlodinium veneficum* has been generating near real-time maps of HABs in the Chesapeake Bay using a hydrodynamic model and satellite data [8]. The methodology uses time of year, salinity, and sea-surface temperature to predict the abundance (low, medium, or high) of the dinoflagellate. The accuracy of these predictions is currently under evaluation. Another group has developed a system of tracking and predicting the spatiotemporal dynamics of the HAB species *Karenia Brevis* in the Gulf of Mexico [9]. The similarity of target objects in consecutive images is used to track the target over time. The system predicts the spatiotemporal dynamics of a bloom using a cellular automaton model to simulate the growth, shrinkage, and collision of blooms under specific wind conditions. This interactive system has been shown to give a 30x speedup over the manual analysis of the image data.

TAOSF will provide the following advantages over existing systems for observing and analyzing HABs:

- Dynamic tasking and adaptation
- Higher in situ resolution and greater insensitivity to cloud cover in comparison with current satellite systems
- Access to and greater agility in coastal waters than what is available through buoys
- Real-time multipoint science data observations and generation of associated interpretations by remotely located oceanographers.

5. HAB SENSING AND CHARACTERIZATION

Our work in this area has two components [10]. First, we are assembling and analyzing all known HAB-related data from the Chesapeake Bay area. Second, for initial sensor testing and validation we have developed a means of producing and ground-truthing a surrogate HAB using rhodamine, a fluorescent compound commonly used as a water tracer dye.

HAB datasets and analysis

The Maryland Department of Natural Resources (DNR) has provided us with descriptions and HAB species cell-count data from five regions in the Chesapeake and Coastal Bays that have experienced algal blooms. We used a Gaussian process approach to predict the cell counts of the dinoflagellate *Karlodinium micrum* from water quality features (temperature, salinity, and dissolved oxygen). The results (Fig. 6) indicate that Gaussian processes using a Gaussian kernel perform just as well as linear regression does for predicting cell counts.

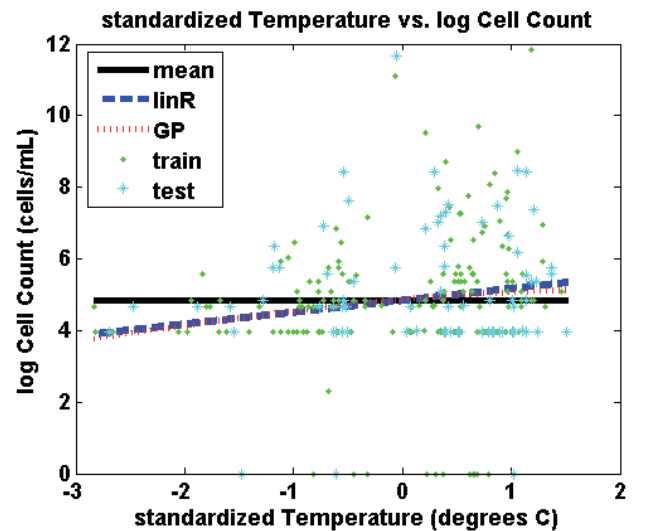


Fig. 6. Predicted log cell counts of *Karlodinium micrum* from temperature using three different algorithms: mean, linear regression (linR), and Gaussian process (GP). The points used for training and testing the algorithms are depicted as green dots and cyan asterisks, respectively.

We also investigated an adaptive sampling approach using the Regional Ocean Modeling System (ROMS) model of the Chesapeake Bay using Gaussian processes to select positions for obtaining sensor measurements to optimally characterize the distribution of salinity from known temperature data. The results (Fig. 7) show the advantage of the adaptive sampling approach over random selection of sampling positions. The mutual information algorithm achieves low RMS error after selecting only a few points to sample and asymptotically approaches the minimum faster than the random selection algorithm [10].

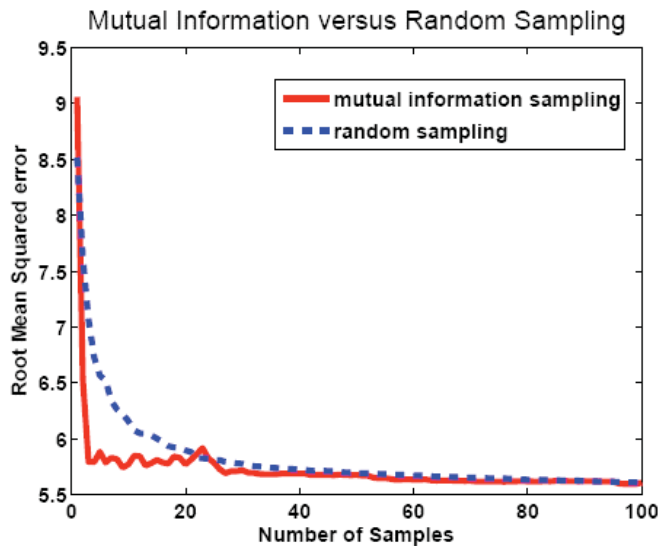


Figure 7. Root Mean Square (RMS) error in selecting points using the Gaussian process-based adaptive sampling approach with the mutual information metric vs. using random selection.

The next step in our analysis will be to integrate MODIS (Moderate Resolution Imaging Spectroradiometer) satellite data (Chlorophyll A and sea surface temperature) with the DNR cell-count data for HAB prediction.

Visual rhodamine dye mapping

Since HABs are sporadic ocean phenomena, we are using rhodamine WT (water-tracing) dye [11] as a HAB surrogate for initial experiments and tests. Because some of the TAOSF system testing and validation is done using an aerial imaging platform (discussed later), it became necessary to correlate aerial dye visibility to dye concentration in the water. This was done by imaging dye diffusion and visibility in a local pond in Pittsburgh [12].

The pond, called Schenley Park Lake (Fig. 8), has a surface area of about 9900m^2 , and a depth conservatively estimated at 1m. The first dye patch, with a concentration of 5ppm, was dispersed from a location at the lower right of the pond, and is shown after 20 minutes of dispersion, when it covered an area of approximately 65m^2 . At this point in time, the patch was still quite visible from an overhead camera but not nearly as intense as the second patch. The latter patch, also with an initial dye surface concentrations of 5ppm, is shown dispersed over a 30m^2 area. Surface

water samples were taken of each patch at measured time intervals and were analyzed using the same fluorometers used on the OASIS platform. This allows us to establish a baseline for correlating camera visibility with in-water concentration measurements.

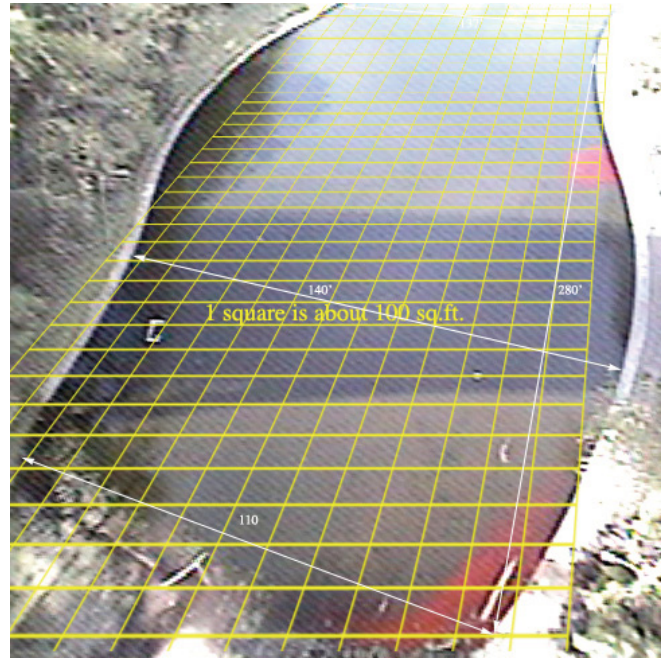


Figure 8. Two dye patches simulating algal blooms. The first (earlier) patch is shown on the lower right, while the second (subsequent) patch is on the upper right. The test was conducted at the Schenley Park Lake in Pittsburgh.

Automated Dye Patch Mapping

In the TAOSF system, we use the Inference Grid (IG) model to represent multiple spatially- and temporally-varying properties. The Inference Grid is a probabilistic multi-property spatial lattice model (a Markov Random Lattice) [13, 14] where sensor information is stored in spatially and temporally registered form, and which is used for both scientific inferences and for vehicle mission planning. The information in each Inference Grid cell is represented as a stochastic vector, and metrics such as entropy are used to measure the uncertainty in the IG [15, 16].

As part of the HAB sensing and characterization effort, we have developed an initial automated dye patch mapping system using the IG model. Overhead imagery of the pond was processed to perform automated cluster identification using an unsupervised clustering algorithm. Using a reference dye spectral signature, the dye dispersion patch was identified and segmented in the image, and a probabilistic metric was associated with the distance to the reference signature in the spectral space. The results for a single pond image is shown in Fig. 9, and for a sequence of images in Fig. 10.

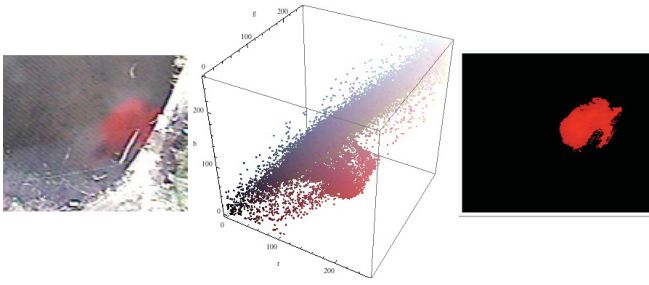


Figure 9. The left image shows the first patch in Fig. 8 after several minutes of dye dispersion. The center plot shows the RGB intensity distributions of the left image; automated image segmentation is done using an unsupervised clustering algorithm. The map on the right shows an Inference Grid with the spatially distributed probabilities of dye being present in the water.

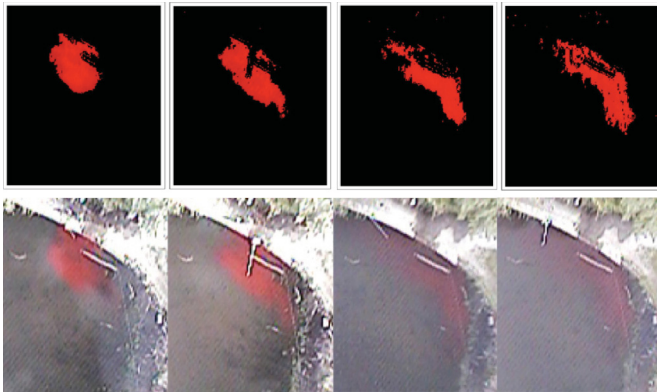


Figure 10. Automated dye patch extent mapping and characterization using the Inference Grid. The images in the bottom row show the first patch in Fig. 8 dispersing over time. The evolution of the corresponding Inference Grid is shown in the upper row, where the spatially and temporally varying dye presence probabilities are shown. The images and maps are rotated counterclockwise (relative to Figs. 8 and 9) for presentation convenience.

6. AERIAL FIELD TEST OBSERVATION PLATFORM

One important component in the field testing and validation process of the overall TAOSF system is the ability to have a “bird’s eye” view of how an algal bloom (or a dye patch) is moving and dispersing in the water, and how the OASIS boats are responding to this process. To address this need, we developed a low-altitude aerial system carrying an avionics package with a recording GPS, barometric altimeter, magnetic compass, serial data link, wide-angle color camera, and transmitter [10, 12]. Fig. 11 depicts a typical deployment and testing configuration, with the OASIS platforms investigating a dye-simulated bloom, and an aerostat carrying the system observation and validation avionics package tethered to a human-piloted chase boat.

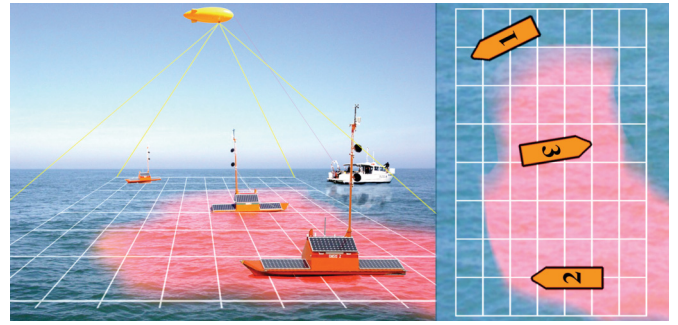


Figure 11. Concept of the TAOSF field validation system: an overhead aerostat (an unmanned blimp tethered to a manned field operations vessel) provides a global visual overview of three OASIS platforms and a patch of rhodamine dye. The overhead map is shown on the right.

The TAOSF aerial observation platform is a 6m long, 2m diameter aerostat (Fig. 12). The aerostat is an unmanned, helium-filled, lighter-than-air (LTA) blimp on a tether. In its current configuration the system is flown unpowered. The onboard avionics package (Fig. 13) is gimballed, and includes a GPS, a barometric altimeter, a magnetic compass, a serial wireless data link, a wide-angle color camera, and a video transmitter. The total weight is 700g.

We emphasize that the aerial observation platform is not currently being used to help identify and track HABs; rather, its purpose is to provide a global view of our field tests to assess the in situ performance of the TAOSF system.



Figure 12. The TAOSF aerostat observation platform. The aerostat is an unmanned, lighter-than-air (LTA) unpowered blimp on a tether. Helium is used for buoyancy. The avionics package (Fig. 13) is mounted below the aerostat.

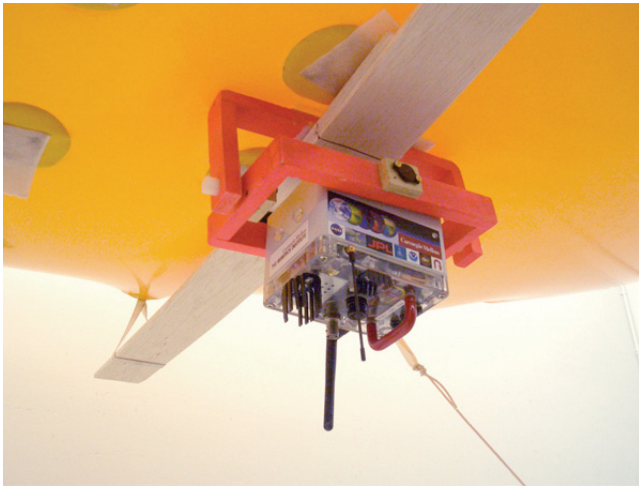


Figure 13. The gimbaled TAOSF observation platform avionics package includes a GPS, a barometric altimeter, a magnetic compass, a serial wireless data link, a wide-angle color camera, and a video transmitter.

7. INTEGRATED SYSTEM TESTING AND VALIDATION

The first integrated in-water tests of the TAOSF architecture were conducted on 27 June and 21 August, 2007. The following discussion focuses on the 21 August test, where a single OASIS boat was used, the aerial observation platform was deployed, and rhodamine dye tracks were laid by a manned chase boat. The aerostat platform was also tethered to the chase boat (Fig. 15). In the sequence we show initial results from this test.

A forward view from the OASIS camera was displayed on the remote operator workstation (Fig. 14), allowing teleoperation of the boat if necessary. The rhodamine tracks laid are shown in Fig. 15.



Figure 14. Forward view from the OASIS boat, as seen from the remote operator workstation.



Figure 15. Aerial view from the aerostat observation platform. The chase boat (with aerostat tether) is in the upper part of the image, the OASIS boat in the lower part, and the rhodamine dye tracks laid by the chase boat are visible towards the right part of the image.

A spiral search pattern was planned and executed by the ASF component of the TAOSF system (Figs. 16 – 18). The operator interface is based in part on the Multi-Robot Operator Control Unit (MOCU) [17]; it displays the boat trajectory, telemetry and position within a satellite map (Fig. 16). The trajectories of both the OASIS boat and the aerostat test observation platform are shown in Fig. 17, and the measured rhodamine dye concentrations along the search path in Fig. 18.

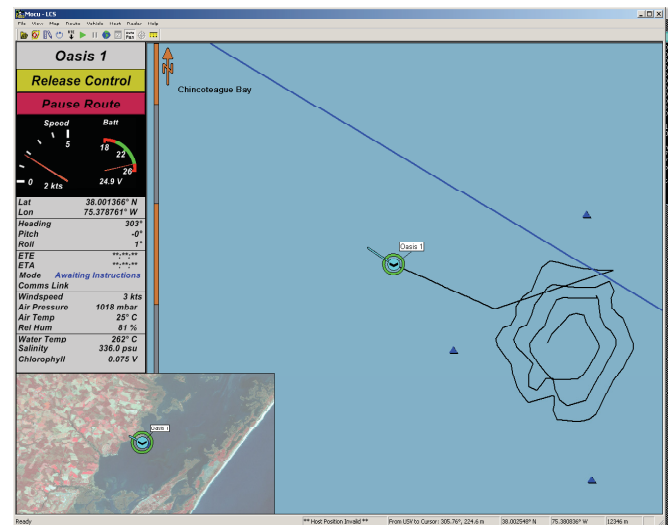


Figure 16. The Multi-Robot Operator Control Unit (MOCU), part of SSA. The right pane shows the spiral search pattern planned and executed by the ASF component of TAOSF. The upper left pane displays the engineering and science telemetry from the OASIS boat, while the lower left pane shows the position of the OASIS platform overlaid on a satellite view of the operating area.



Figure 17. A satellite view of the August 21 field test area. The GPS track of the OASIS boat is shown in red, while the aerostat observation path (obtained from the onboard avionics) is shown in white.



Figure 18. A slanted view of the ocean area where the test was conducted. The measured rhodamine concentrations are shown as a vertical “ribbon” along the route taken by the OASIS boat (as shown in Figs. 16 and 17).

8. CONCLUSIONS AND FUTURE WORK

This paper describes a telesupervision architecture for multiple autonomous platforms and its application to the particular problem of the detection of harmful algal blooms. Initial work has concentrated on the integration of subsystems developed by the collaborating organizations, in the development of HAB and dye observation systems, and in building an aerial platform to allow observation of the TAOSF system and the OASIS boats from the air. In-water tests have demonstrated the viability of the TAOSF architecture.

One of our key next steps is an extended end-to-end test in which multiple OASIS platforms map a rhodamine-dye

HAB surrogate under human telesupervision. Over the next year we plan to increase the number of platforms, develop and deploy adaptive sensing algorithms, and continue deploying the TAOSF system in the Chesapeake Bay estuary.

Because of their in-situ observation capabilities and resolution, as well as their adaptivity, telesupervised autonomous surface vehicles are crucial to the sensor web for Earth science. The telesupervision architecture underlying TAOSF is broadly applicable to a wide variety of domains beyond HABs, including ecological forecasting, water management, carbon management, disaster management, coastal management, homeland security, and planetary exploration.

ACKNOWLEDGMENTS

This work was supported by NASA award NNX06AF27G, “Telesupervised Adaptive Ocean Sensor Fleet”, granted under the Advanced Information Systems Technology program of NASA’s Earth Systems Technology Office (ESTO). The TAOSF project is a collaboration among Carnegie Mellon University (CMU), NASA Goddard Space Flight Center (GSFC), NASA Goddard’s Wallops Flight Facility (WFF), Emergent Space Technologies, Inc. (EST), and the Jet Propulsion Laboratory (JPL), California Institute of Technology. Work on the OASIS platforms is conducted by Emergent Space Technologies, Inc., EG&G, and Zinger Enterprises under award NA03NOS4730220 from the National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce.

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BIOGRAPHY



Dr. Alberto Elfes is a Principal Member of Technical Staff in the Mobility and Robotics Systems Section at NASA's Jet Propulsion Laboratory (JPL). He leads projects in the areas of autonomous aerial vehicles for planetary exploration, coordination and control of robot/robot and robot/human teams, and space mission planning and architecture optimization. He has held positions as Director of the Automation Institute, Brazil, and as a research scientist at the IBM T. J. Watson Research Center, the Engineering Design Research Center and the Robotics Institute, CMU. Additionally, he has held university professorships in Brazil and Germany. He has an E.Eng. degree in Electronics Engineering and an M.Sc. degree in Computer Science from the Aeronautics Institute of Technology (ITA), Brazil, and a Ph.D. degree in Electrical and Computer Engineering, with concentration in Robotics, from Carnegie-Mellon University. Dr. Elfes has over 100 publications in international journals, conferences and books, and has lectured extensively in North America, Europe, Brazil and Japan. He is a recipient of the Mercator Professorship Award of the German Research Foundation (DFG).